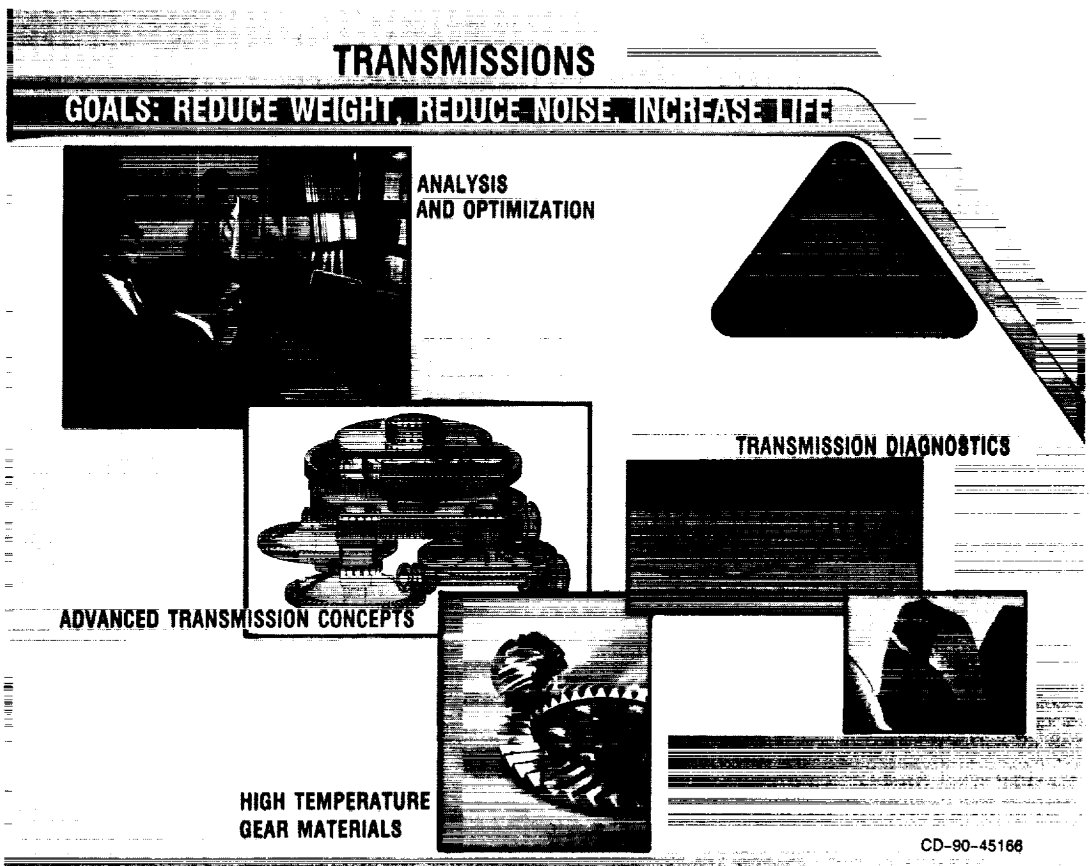
529

0802

ADVANCED ROTORCRAFT TRANSMISSION TECHNOLOGY

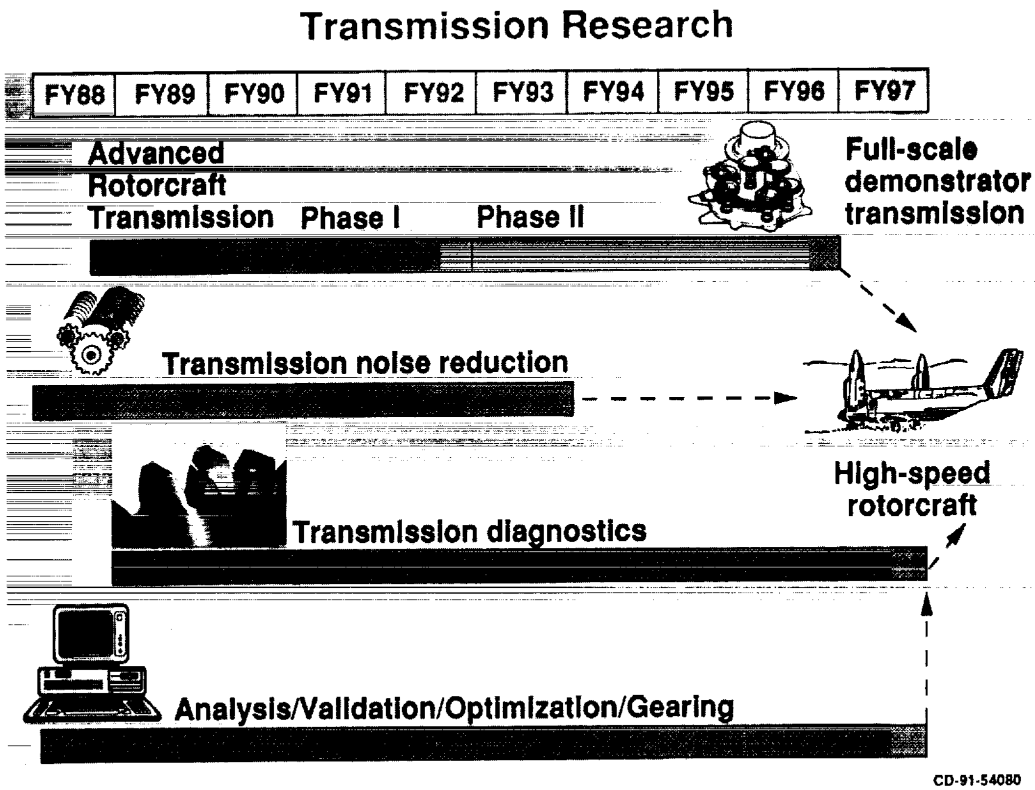
David G. Lewicki
Propulsion Directorate
U.S. Army Aviation Systems Command
NASA Lewis Research Center
Cleveland, Ohio

The NASA Lewis Research Center and the Propulsion Directorate of the U.S. Army Aviation Systems Command are involved in a joint research program to advance the technology of rotorcraft transmissions. The program consists of analytical and experimental efforts to achieve the overall goals of reducing transmission weight and noise, while increasing life and reliability. The work includes in-house studies and tests, university grants, industry contracts, and joint programs with other military organizations. This paper highlights recent activities in the areas of transmission and related component research. Three major activities are highlighted: the Advanced Rotorcraft Transmission (ART) program, a comprehensive transmission noise reduction program, and a transmission diagnostics research effort. Results of recent activities are presented along with future research plans.



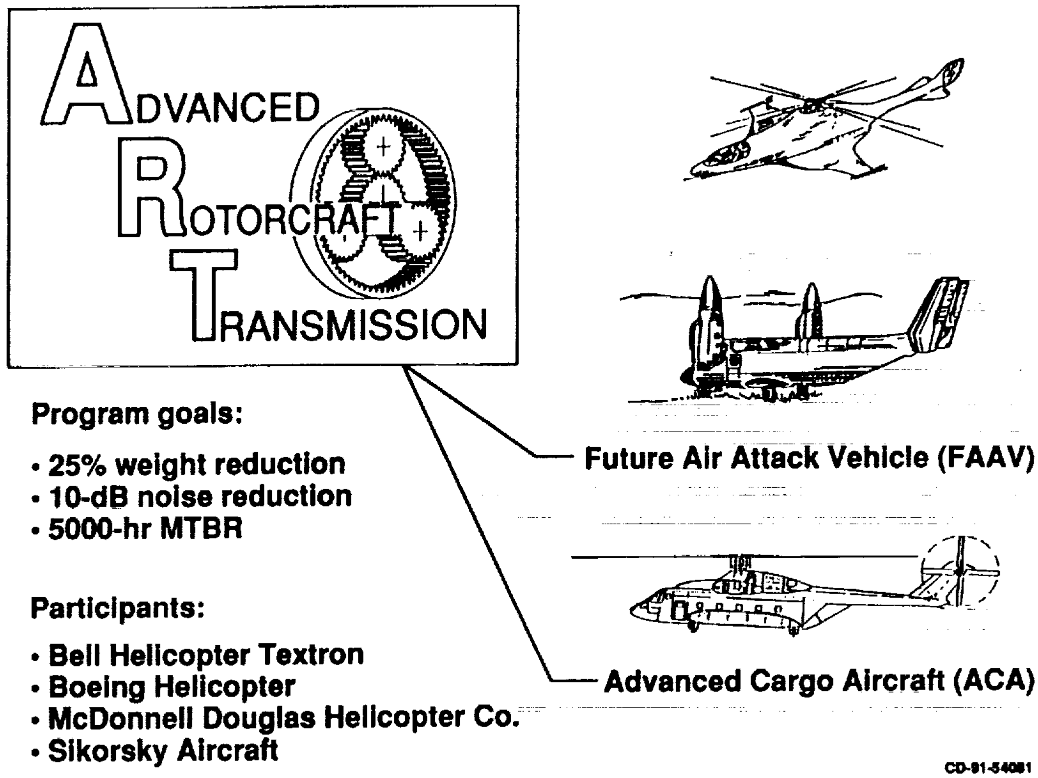
Joint rotorcraft transmission research began in 1970 with the NASA Lewis Research Center and the Propulsion Directorate of the U.S. Army Aviation Systems Command, and continues to the present (refs. 1 to 8). The major goals of the program are to increase the life, reliability, and maintainability; reduce the weight, noise, and vibration; and maintain the relatively high mechanical efficiency of the drive train in helicopter and turboprop transmissions. Lighter transmissions increase vehicle range, payload, and performance. Higher life and reliability produce safer operation and lower operating costs. Quieter transmissions increase pilot and passenger safety and comfort. The approach in achieving these goals is to identify advanced materials and lubrication schemes, as well as advanced design concepts and analyses for both transmission components and total transmission systems. The research efforts consist of in-house projects, university grant work, and industry-contracted efforts. Unique experimental testing facilities for transmissions exist at Lewis (ref. 9) for verifying analytical codes as well as demonstrating advanced design concepts and testing mechanical components, materials, and lubrication techniques.

The purpose of this paper is to review the current helicopter transmission research at Lewis. Results of recent activities are presented along with future research plans. The emphasis of the reported work is on three current activities: (1) the Advanced Rotorcraft Transmission (ART) program, (2) a comprehensive transmission noise reduction program, and (3) a newly developed effort in transmission diagnostic research.



The ART program is intended to develop and demonstrate lightweight, quiet, and reliable drive train systems for next-generation Army rotorcraft. This program is primarily a contracted effort with some Lewis in-house technical support and testing. The ART program started in fiscal year 1988 with phase I (Preliminary Design and Component Validation), and phase II (Full-Scale Demonstrator) should be completed by fiscal year 1997. The goal of the transmission noise reduction program is to reduce the gearbox noise by 10 dB in the next generation of transmissions for advanced rotorcraft. This effort, which started in 1988, is a mixture of university grant activities and in-house analysis and experimental studies. It is anticipated that by 1994 an acoustic computer code for transmissions will be developed and validated. Transmission diagnostic research at Lewis is a rather new effort which started around 1989. The objective is to evaluate and develop diagnostic methods for early detection of incipient failures of critical drive train components. The long term goal is to demonstrate a transmission health and monitoring system by 1998.

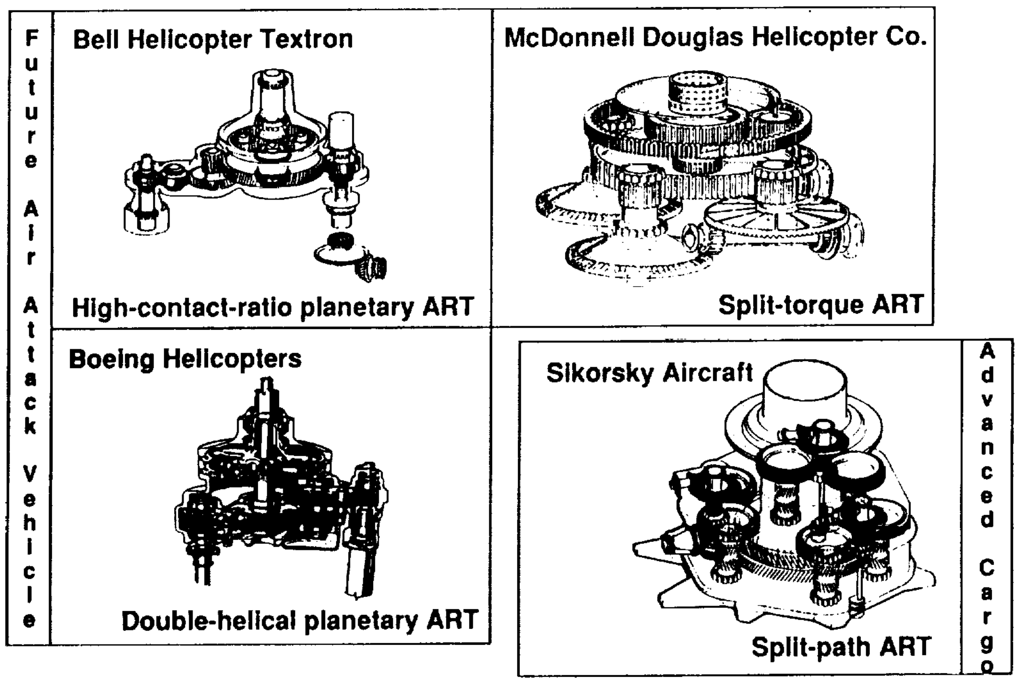
The research efforts described above are complemented with basic research projects in gearing, analysis and validation of transmission components, and optimization. A unique data base has been established using the NASA Spur Gear Fatigue Test Apparatus, supplying valuable data on gear materials, lubrication, and life analysis. Cooperative programs with other military organizations exist, such as the Navy/NASA/Army Advanced Lubricants Program, with the goal of developing a separate transmission lubricant with improved load-carrying capacity, higher temperature capabilities, and corrosion resistance. In addition, analytical codes are being developed for gear, bearing, and transmission systems in the areas of dynamics, life, and mechanical performance.



The Advanced Rotorcraft Transmission (ART) program is an Army funded, joint Army/NASA program. Its intent is to develop and demonstrate lightweight, quiet, durable drive train systems for next generation rotorcraft (ref. 10). ART addresses general requirements of two distinct next-generation aircraft classes: (1) the Future Air Attack Vehicle, a 10 000- to 20 000-lb aircraft capable of undertaking tactical support and air-to-air missions, and (2) the Advanced Cargo Aircraft, a 60 000- to 80 000-lb aircraft capable of heavy-lift field support operations. The ART program includes both tiltrotor and more conventional helicopter configurations. Its specific objectives include reducing the drive train weight by 25 percent (compared with baseline state-of-the-art drive systems configured and sized for next-generation aircraft), reducing the noise level at the transmission source by 10 dB relative to the suitably sized and configured baseline, and increasing mean time between removal (MTBR) to 5000-hr.

ART consists of two phases. The first is the Preliminary Design and Component Validation phase. Here, new ideas in gear configuration, transmission concepts, and airframe/drive train integration are being studied. Also included is the application of the latest available component, material, and lubrication technologies. Contract participants include McDonnell Douglas Helicopter Company, Boeing Helicopters, Bell Helicopter Textron, and Sikorsky Aircraft. The Lewis Research Center is also providing in-house technical support and testing. The second phase of the ART program is the Full-Scale Demonstrator phase where a full-size version of the transmission designated in phase I will be designed in detail and tested to demonstrate the goals of the program.

Advanced Rotorcraft Transmission Program
Advanced Transmission Configurations



CD-91-54082

All four ART contractors have selected their vehicle application, baseline aircraft, and baseline transmission. Candidate drive train systems have been developed to a conceptual design stage. Tradeoff studies based on comparative weight, noise, and reliability have resulted in selection of the ART transmission for each of the four participating contractors. Preliminary designs of each of the four selected ART transmissions have been completed, as have mission impact studies. Comparisons of aircraft mission performance and life cycle costs were undertaken for next-generation aircraft with ART and with the baseline transmission.

McDonnell Douglas Helicopter Company (MDHC) selected the Future Air Attack Vehicle (FAAV). They defined their baseline as an upgraded AH-64 Apache helicopter and chose a split-torque transmission with face gears as their advanced technology configuration (ref. 11). Boeing Helicopters chose the FAAV application and a tilt-rotor aircraft as their baseline. They selected a helical three-stage planetary configuration for ART (ref. 12). Bell Helicopters also selected the FAAV application and a tilt-rotor aircraft as their baseline, but they chose a high-contact ratio planetary configuration for ART (ref. 13). Sikorsky Aircraft was the only participant to select the Advanced Cargo Aircraft application. They chose an upgraded CH-53 helicopter as their baseline and a split-path configuration for ART (ref. 14). All four contractors have projected that the ART goals for weight, noise, and life are attainable. All contractors deduced from the mission analysis that huge savings in life cycle costs could be achieved if an advanced transmission design is incorporated in the aircraft during development of the airframe.

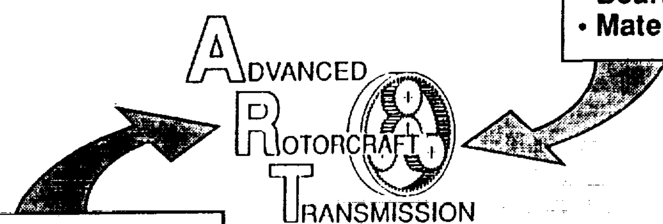
Advanced Rotorcraft Transmission Program
Planned Component Testing

Milestones completed:

- Key component technologies identified
- Component test plans developed

Contractor Tests

- 1/2 size split-path transmission
- Planetary tests
- Gear tests
- Bearing tests
- Materials tests



Lewis in-house tests

- Low-noise spur and spiral bevel gear tests
- Face gear tests

Significance:

- Identification permits testing to demonstrate capability to attain weight, noise, and life goals.

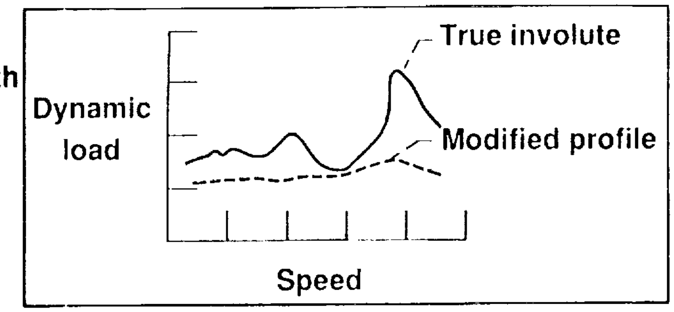
CD-91-54083

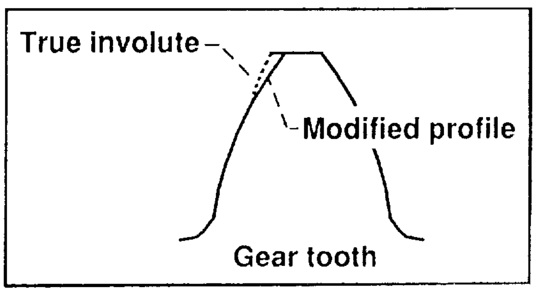
For these ART configurations to meet the program goals, certain critical component technologies must be incorporated into the preliminary designs. MDHC plans to perform single-tooth bending tests, gear scoring tests, impact toughness tests, and fracture toughness tests for a variety of advanced gear materials manufactured using near-net-shape gear forging to improve strength and reduce manufacturing costs. In addition, Lewis and MDHC have established a joint program to test face gears in the NASA Spiral Bevel Rig. Boeing Helicopters plans to test gears made from Vasco X-2 high-temperature material and manufactured using near-net-shape forging. They also plan to test lightweight titanium accessory drive gears with treated surfaces. Lewis and Boeing will jointly evaluate noise generation properties of eight parallel-axis gear configurations in the NASA Gear Noise Test Rig. In addition, Boeing has planned substantial hybrid bearing and active noise cancellation tests. Bell Helicopter is concentrating their component test program in three major areas: planetary gear train tests, material tests, and spiral bevel gear tests. The planetary gear train will be tested for noise and vibration, efficiency, fatigue, and loss of lubricant. Lewis and Bell have established a joint program to test spiral bevel gears in the NASA 500-hp Test Stand. Sikorsky Aircraft will test a scaled-down version (one-half size) of the split-path transmission configuration proposed for the Advanced Cargo Aircraft. Included in the testing are the following: high-contact-ratio double-helical gears on the output stage, double-helical pinions with large gear tooth face width-to-diameter ratios, an elastomeric torque-sharing device, topological gear tooth profiling for improved load distribution, high-temperature operation (300 °F), scoring-resistant X-53 gear material, and transmission error measurements.

Gear Tooth Profile Studies

Milestones completed

- **Comprehensive analytical study of effect of gear tooth profile on dynamic loads completed.**
- **Experimental verification plan established; test gears ordered.**





Significance:

- **Slight modification of gear tooth profile produces significant change in dynamic load.**
- **Dynamic loads can be significantly reduced through optimized gear tooth profiles.**

CD-91-54084

Helicopter noise and vibration are important topics because of health and environmental concerns, passenger comfort, and pilot efficiency. As power increases so does the weight penalty associated with cabin soundproofing materials. These facts have led to an effort to reduce noise and vibration at their origin. Today the main source of noise in helicopter interiors is the gear mesh in the transmission. The goal of the NASA Lewis transmission noise reduction program is to reduce the gearbox noise by 10 dB in next-generation transmissions for advanced rotorcraft (ref. 15).

Gear dynamic loading in rotorcraft transmissions is a major source of noise. Gear dynamic loading is caused by a complex interaction between the various gears in mesh and also the dynamic properties of the bearings, shafts, housings, and masses in the system. Gear dynamic load is caused by the unsteady relative angular motion of gear pairs. Not only is it a major source of noise, but it can significantly reduce component life. The computer program DANST (Dynamic ANalysis of Spur gear Transmissions) was used to investigate the effects of both linear and parabolic tooth profile modifications on the dynamic response of low-contact-ratio spur gears (refs. 16 and 17) and high-contact-ratio gears (refs. 18 and 19). The dynamic loading response of unmodified (perfect involute) gear pairs was compared with that of gears with various profile modifications. The effects of the total amount of modification and the length of the modification were studied at various loads and speeds to find the optimal profile to minimize dynamic loading and noise. Then, normalized design charts were generated for gear systems operating at various loads and tooth modifications. The amount and type of tooth profile modification had a significant effect on the predicted dynamic response.

Gear Noise Rig–Facility Design and Installation

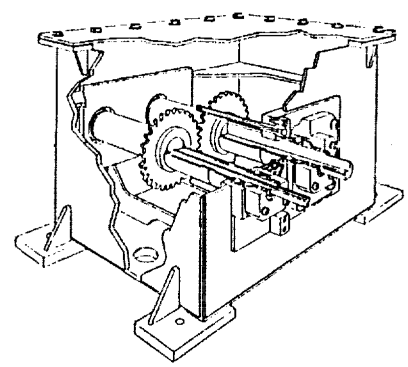
Gear Noise Rig

Milestones completed:

- **Design and fabrication of highly instrumented test gearbox**
- **Test rig designed and constructed**
- **Facility is fully operational**

Significance:

- **Parametric studies of gear design variables**
- **Verification of computer models for gear dynamics and noise**
- **Technology base for future quiet transmission design**



Test Gearbox

CD-91-54085

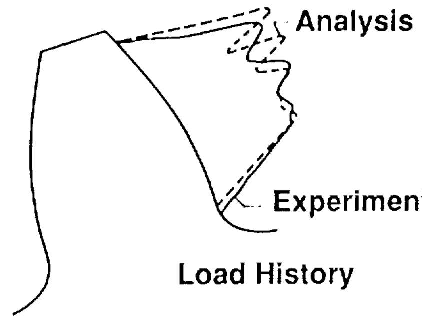
As previously mentioned, extensive studies have been performed to reduce gear dynamic loading, and consequently, lower overall transmission noise. Work has also resulted in the development of several computer codes and analyses. A finite element model of a geared rotor system with flexible bearings was developed (ref. 20). The program is capable of calculating the natural frequencies, corresponding mode shapes, and the dynamic loads at various positions in the system when excited by mass imbalance, geometric eccentricities, and transmission errors. An understanding of the interaction between the gear mesh and housing dynamics is also a crucial step in the overall plan of reducing vibration and noise in rotorcraft transmissions. One study analyzed the dynamics of the gear housing from the NASA Gear Noise Rig using both finite element analysis and experimental modal analysis (ref. 21). Another study concentrated on the complex transmission of vibration through rolling element bearings and resulted in the development of a new methodology for modeling transmissibility of vibration (ref. 22). In addition, the acoustic intensity program BEMAP (Boundary Element Method for Acoustic Prediction) was adapted to predict the sound field of a gearbox (ref. 23).

These new computer codes and analyses will form an important design tool for meeting the noise reduction goals. As a method to verify the codes, the NASA Gear Noise Rig was recently installed at Lewis. This rig will allow studies of gear design parameters and their effect on dynamic loads, vibration and noise production, propagation, and radiation. It will measure the effects on dynamic loads and noise caused by tooth profile, tooth spacing errors, gear misalignment, and damping.

Gear Dynamics Code Validation

Milestones completed:

- Compared analysis and experiment
- 28 test conditions
- Successfully predicts dynamic loads
- NASA TM-103232



Significance:

- Experimental verification of gear dynamics code
- Allows tuning gear profile for minimum noise and vibration

CD-91-54086

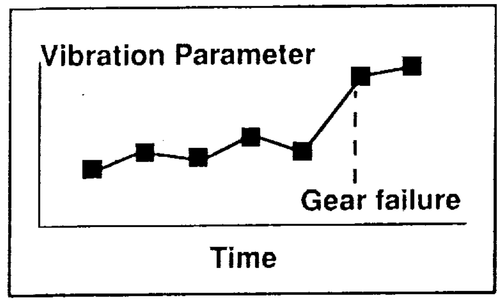
Gear vibration is primarily caused by the abrupt transition of the load from tooth to tooth as the gears mesh. The profiles of gear teeth are often modified to help smooth this dynamic action. The effects of tooth profile modification on gear dynamics is simulated by several computer codes developed through NASA grants and contracts. There has been an acute need to verify the gear dynamic load prediction codes with experimental data taken under carefully controlled conditions. The goal of this initial effort was to verify predictions of the gear dynamics code DANST for both the gear tooth loads and for the bending stress at the gear tooth root. Gear dynamics experiments were conducted in the NASA Gear Noise Rig. These tests were completed on a pair of standard involute spur gears with a linear profile modification run at a variety of speed and load conditions (ref. 24). Strain gages were used to measure the dynamic force acting between gear teeth, and the experiments were compared with the analysis.

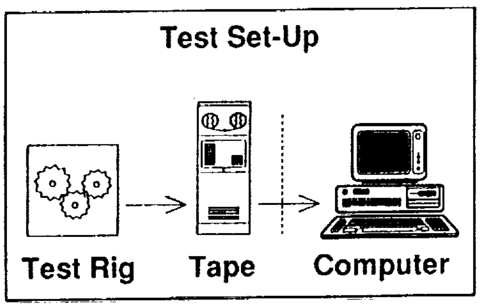
The maximum dynamic load prediction from DANST generally agreed with measurement results within 6 percent. The bending stresses predicted from DANST generally agreed with measurement results within 10 to 15 percent. The analysis also successfully predicted loss of tooth contact that occurred when the gears were run at high speeds and with a light load. The validated code will thus allow a gear designer to tune the profile of a new gear to minimize dynamic loads and stress, with the potential to reduce noise and vibration without expensive and time-consuming hardware testing. The code will also predict the effects of load and speed on the dynamics of a gear system.

Gear Failure Prediction Studies

Milestones completed:

- Vibration signatures of various modes of gear failures collected.
- Signatures analyzed using several failure prediction techniques.





Results:

- Algorithms to predict gear failures identified.
- Gear, bearing, and housing modal properties affected results.

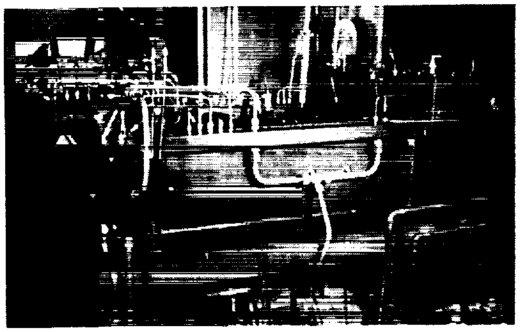
CD-91-54087

There has been a recent interest in transmission diagnostics for both safety and economy. A comprehensive transmission diagnostics program, of both basic and applied research, is being developed at Lewis. The basic research consists of evaluation and development of new and improved transmission component failure prediction techniques. The applied research consists of evaluating existing commercially available diagnostic devices by using the unique facilities at Lewis.

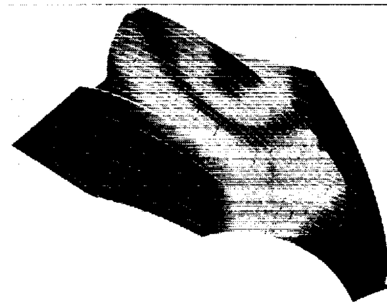
As an initial study, vibration signatures from 11 gear sets that were run from start to failure were collected from instrumentation installed on a single mesh gear fatigue test stand (ref. 25). Several gear mesh failure prediction methods were applied to the data to determine if a correlation existed between the various techniques and the observed modes of failure. The gear failures consisted of heavy wear and scoring, tooth breakage, single tooth pitting, and distributed pitting over several teeth. Results showed that the prediction methods were able to detect those gear failures which involved heavy wear or distributed pitting. Also, the modal frequency response between the gear shaft and transducer was found to significantly affect the vibration signal.

Future plans include installation of an on-line computer-based system on the single-mesh gear fatigue test stand and the 500-hp Transmission Test Stand. The objective will be to continue to evaluate the most promising gear failure detection algorithms and to develop new methods where needed. Oil debris monitoring methods will also be investigated as a diagnostic tool.

Spiral Bevel Gear Analysis and Experiments



Bevel Gear Rig



Computer Model

Test Specimen

- Tooth geometry and kinematic analysis
- Tooth contact analysis
- Finite element analysis
- Fatigue testing
- Noise/vibration testing
- Lubrication testing

CD-91-54088

In addition to the ART program, the transmission noise reduction program, and the diagnostics research, there are basic research efforts in gearing analysis and validation. One such effort is the work on spiral bevel gears. Advanced analytical capabilities such as finite element analysis are becoming commonplace in the design and development of components for next-generation rotorcraft. However, such techniques are not very straightforward for spiral bevel gears because of the complex tooth geometry considerations. Methods are being developed to use the gear geometry results for spiral bevel gears and merge the data with the current finite element code (ref. 26). The tooth coordinates and loading are input to a commercially available solid modeling package, PATRAN, for pre- and post-processing. Currently, the finite element analysis code NASTRAN is being used. The result is an in-depth stress and deflection analysis for spiral bevel gears, a valuable tool for the designer.

To verify analytical predictions and to improve the basic understanding of spiral bevel gear operation, the NASA Spiral Bevel Gear Rig is being used. Currently, the facility is being configured to conduct transient temperature tests. These tests will closely examine lubrication parameters such as oil temperature, flow, and oil jet orientation and will determine their effect on gear surface temperature. Critical parameters regarding efficient lubrication of high-speed spiral bevel gear systems will be investigated and identified. After these tests, material effects on spiral bevel gear fatigue life will be studied. Spiral bevel gears manufactured from six different materials are available for testing. The results of these tests will be compared with the extensive data base collected for spur gears to see if there is a correlation between parallel axis and spiral bevel gear life experiments.

CONCLUDING REMARKS

The purpose of this paper was to review the significant accomplishments of the past few years in helicopter transmission technology that have resulted from NASA/Army research activities at the NASA Lewis Research Center. Research program goals were to reduce transmission weight and noise and to increase life and reliability. A variety of analytical and experimental studies from in-house activities, university grants, and industry contracts were presented. Significant transmission weight reduction potentials were identified through the use of novel configuration arrangements and/or advanced components. Transmission life improvement potentials were identified through the use of advanced materials, lubrication, and component design.

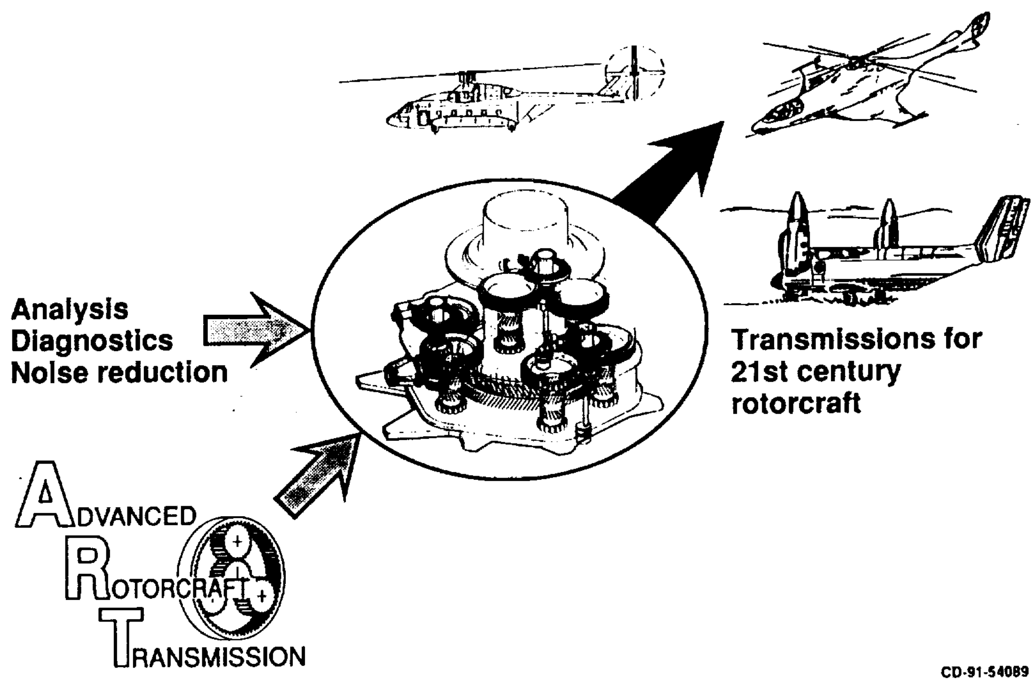
An important new initiative called the Advanced Rotorcraft Transmission (ART) program began in 1988. The intent of the program is to develop advanced concept transmissions for two categories of future Army rotorcraft: the Future Air Attack Vehicle and the Advanced Cargo Aircraft. The program parallels the concept offered by engine demonstration programs and will provide a way for the industry to develop advanced concepts and trial designs well in advance of critical needs.

An initial finding of the Advanced Rotorcraft Transmission (ART) program was that a generalized, comprehensive, noise prediction methodology for transmissions did not exist at the time of the configuration tradeoff studies. During these studies, baseline transmission noise data were used as a starting point. Extrapolation to each of the ART candidates was accomplished by comparing number of gear meshes, mesh loading, gear geometry features, and mesh speeds with those of the baseline. The result was typically a very qualitative comparison with a net judgment for each candidate as to whether it would be better, worse, much better, much worse, or the same as the baseline. Goals of the ongoing NASA transmission noise reduction program are to increase the basic understanding of the complex noise generation and transmissibility phenomena and to develop accurate, analytical tools for noise prediction. This will aid in the overall goal of reducing transmission noise and become a basis for next-generation design.

Transmission and drive train problems are major factors in vehicle maintenance costs and are a significant and costly cause of rotorcraft accidents, fleet groundings, and mission aborts. Drive trains must be periodically inspected, requiring a major disassembly of the transmission for close inspection. Transmission health monitoring can improve the safety of helicopter flight and improve maintenance efficiency. The Lewis diagnostics research combines analytical and experimental efforts to evaluate and develop methods for early detection of component failures.

It is reasonable to expect that rotorcraft will continue to evolve in the future. To achieve the necessary advances in rotary wing flight capabilities, drive train technology must keep pace with advances in engines, controls, structures, and rotors. The current plan for NASA/Army transmission research calls for a continued reduction in weight and noise, an increased emphasis in diagnostics, and continued support of military and civilian aviation activities. The overall intent is to provide technology readiness in transmissions for 21st century high-speed rotorcraft.

Summary


Analysis
Diagnostics
Noise reduction
Transmissions for
21st century
rotorcraft
ADVANCED
ROTORCRAFT
TRANSMISSION
CD-91-54089

REFERENCES

1. Zaretsky, E.V.; Townsend, D.P.; and Coy, J.J.: NASA Gear Research and Its Probable Effect on Rotorcraft Transmission Design. NASA TM-79292, 1979.

2. Zaretsky, E.V.; Coy, J.J.; and Townsend, D.P.: NASA Transmission Research and Its Probable Effects on Helicopter Transmission Design. NASA TM-83389, AVRADCOM-TR-83-C-3, 1983.

3. Advanced Power Transmission Technology. G.K. Fischer, ed., NASA CP-2210, AVRADCOM-TR-82-C-16, 1983.

4. Weden, G.J.; and Coy, J.J.: Summary of Drive-Train Component Technology in Helicopters. NASA TM-83726, USAAVSCOM-TR-84-C-10, 1984.

5. Coy, J.J.; Townsend, D.P.; and Zaretsky, E.V.: Gearing. NASA RP-1152, AVSCOM-TR-84-C-15, 1985 (Chapter 38 in Mechanical Design and Systems Handbook, H. Rothbart, ed., McGraw-Hill, 1985).

6. Coy, J.J.: Rotorcraft Transmission. Aeropropulsion '87, E.A. Willis, Jr., ed., NASA CP-3049, 1987, pp. 303-314.

7. Coy, J.J.; and Bill, R.C.: Advanced Transmission Studies. NASA TM-100867, AVSCOM-TR-88-C-002, 1988.

8. Lewicki, D.G.: Transmission Research Activities at NASA Lewis Research Center. NASA TM-103132, AVSCOM-TM-90-C-006, 1990.

9. Lewicki, D.G.; and Coy, J.J.: Helicopter Transmission Testing at NASA Lewis Research Center. NASA TM-89912, AVSCOM-TR-87-C-10, 1987.

10. Bill, R.C.: Advanced Rotorcraft Transmission Program. NASA TM-103276, 1990.

11. Bossler, R.B.; and Heath, G.F.: Advanced Rotorcraft Transmission (ART) Program Status. Presented at the American Helicopter Society Rotary Wing Propulsion Specialists Meeting, Williamsburg, VA, Nov. 13-15, 1990. Preprint No. 4.

12. Lenski, J.W.: Boeing Helicopters Advanced Rotorcraft Transmission (ART) Program Status. Presented at the American Helicopter Society Rotary Wing Propulsion Specialists Meeting, Williamsburg, VA, Nov. 13-15, 1990. Preprint No. 2.

13. Henry, Z.S.: Preliminary Design and Analysis of an Advanced Rotorcraft Transmission. Presented at the American Helicopter Society Rotary Wing Propulsion Specialists Meeting, Williamsburg, VA, Nov. 13-15, 1990. Preprint No. 3.

14. Kish, J.G.: Advanced Rotorcraft Transmission (ART) Program Review. Presented at the American Helicopter Society Rotary Wing Propulsion Specialists Meeting, Williamsburg, VA, Nov. 13-15, 1990. Preprint No. 5.

15. Zakrajsek, J.J., et al.: Gear Noise, Vibration, and Diagnostic Studies at NASA Lewis Research Center. NASA TM-102435, AVSCOM-TR-89-C-020, 1990.

16. Lin, H.H.; Townsend, D.P.; and Oswald, F.B.: Profile Modification to Minimize Spur Gear Dynamic Loading, NASA TM-89901, 1988.

17. Lin, H.H.; Oswald, F.B.; and Townsend, D.P.: Dynamic Loading of Spur Gears With Linear or Parabolic Tooth Profile Modifications. NASA TM-101444, AVSCOM-TR-88-C-003, 1989.

18. Lee, C., et al.: Influence of Linear Profile Modification and Loading Conditions on the Dynamic Tooth Load and Stress of High Contact Ratio Gears. NASA TM-103136, AVSCOM-TM-90-C-004, 1990.

19. Lin, H.H., et al.: Computer-Aided Design of High-Contact-Ratio Gears for Minimum Dynamic Load and Stress. NASA TM-103275, 1991.

20. Kahraman, A., et al.: Dynamic Analysis of Geared Rotors by Finite Elements. NASA TM-102349, AVSCOM-TM-89-C-006, 1990.

21. Lim, T.C.; Singh, R.; and Zakrajsek, J.J.: Modal Analysis of Gear Housing and Mounts. NASA TM-101445, AVSCOM-TR-88-C-041, 1989.

22. Singh, R.; and Lim, T.C.: Vibration Transmission Through Rolling Element Bearings in Geared Rotor Systems. NASA CR-4334, AVSCOM-TR-90-C-019, 1990.

23. Seybert, A.F.; Wu, T.W.; Wu, X.F.; and Oswald, F.B.: Acoustical Analysis of Gear Housing Vibration. NASA TM-103691, 1991.

24. Oswald, F.B., et al.: Comparison of Analysis and Experiment for Dynamics of Low-Contact-Ratio Spur Gears. NASA TM-103232, AVSCOM-TR-90-C-017, 1991.

25. Zakrajsek, J.J.: An Investigation of Gear Mesh Failure Prediction Techniques. NASA TM-102340, 1989.

26. Handschuh, R.H.; and Litvin, F.L.: A Method for Determining Spiral Bevel Gear Tooth Geometry For Finite Element Analysis. NASA TP-3096, 1991.